

Theoretical Studies of Volatile Processes in the Outer Solar System

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Triton Surface-Atmosphere Interactions

In collaboration with Roger Yelle and Donald Hunten, a study was undertaken to understand the energy and mass couplings between the surface and atmosphere of Triton. Consideration of the role of thermal conduction, eddy mixing, condensation and radiative heating in the thermal balance of the lower atmosphere results in the conclusion that the temperature gradient is negative in the lower atmosphere but becomes positive at higher altitudes. The negative temperature gradient is caused by eddy mixing, which drives the temperature towards the dry adiabat. The positive gradient at higher altitudes is a result of the downward conduction of heat produced in the ionosphere. The low concentrations of thermally active molecules and small aerosol optical depths imply that radiative processes have a negligible effect on the thermal structure. We show that this temperature profile is reasonably consistent with the data from the Voyager radio-occultation experiment, but different from the standard interpretation of these data. Based on the height of the geyser-like plumes seen by Voyager we suggest that the convective and conductive regions of the atmosphere join at the tropopause near 10 km. Rather modest geyser action in the subliming nitrogen ice cap triggers moist convective plumes (figure 1) which must have diameters of at least 1 km and may have velocities up to 100 m/sec; they stop within about 1 km of the tropopause (1).

A model of volatile transport on Triton's surface was constructed in collaboration with J.A. Stansberry, Carolyn C. Porco and Alfred McEwen. We used Voyager imaging data to constrain the albedo variation across the surface and incorporate these in a thermal balance model involving insolation, reradiation and latent heat of sublimation of nitrogen ice. The model predicts that Triton's surface north of 15° north latitude is experiencing deposition of nitrogen frosts, as are the bright portions of the south polar cap near the equator. This result potentially explains why the south cap covers nearly the entire southern hemisphere of Triton (2)

Numerical models of the Evolution of Titan's Surface and Atmosphere

Chris McKay, James Pollack, Regis Courtin and the author completed a coupled ocean-atmosphere model of Titan. The atmospheric model is based on the Ames 1-D non-grey radiative-convective simulation, and represents a higher-fidelity atmosphere model than that used previously. The ocean model is self-consistently coupled to the atmosphere in that the partitioning of the available inventory of volatiles (i.e., N_2 , CH_4 , and C_2H_6) is determined by the computed temperature. We also considered a surface model in which an ocean was absent, but small methane lakes were included. The decreased solar luminosity over time is also included. Several cases for the initial volatile inventory of methane are considered (corresponding to various possible present-day relative humidities). We find that in general temperatures on the surface of Titan were 10-20K cooler than at present, and that the spectral properties of the IR gaseous absorbers in the 400-600 cm^{-1} window in the thermal infrared determine the response of the surface temperature to changing solar luminosity. We find a similitude between the climate-controlling roles of methane on Titan and water on Earth, and between molecular hy-

drogen on Titan and carbon dioxide on Earth. The former gases are strong greenhouse gases that are limited by condensation, while the latter are trace gases which play a key role in closing major infrared windows.

Rheology of Ammonia-Water Liquids

A collaboration with Jeff Kargel, Steve Croft and John Lewis has concerned experimental and theoretical study of the rheological properties of ammonia-water and ammonia-water-methanol liquids and crystal-liquid slurries. The viscosities of the liquid mixtures examined in this work are much greater than would be expected based on the assumption that the endmember models are non-interactive; in combination with molar volume and vapor pressure data this indicates that the liquid is highly structured (figure 2). With supercooling and/or partial crystallization, these liquids/slurries may attain viscosities ranging up to 10^6 poise or higher. The results were applied to the icy satellites of the outer solar system (including Triton), on which a number of regions have features which could be interpreted as volcanic in origin. While the enormous variation in morphology of flow features requires a great range in rheological properties at the time of eruption, these properties are nonetheless within the range of viscosities for likely compositions. Even some of the more viscous flows can be explained by partially-crystallized binary materials (e.g., ammonia-water), or ternary mixtures with (e.g.) methanol (3).

Chemical evolution of interstellar grains

In a collaboration with Steffi Engel and Bashar Rizk, we examined the frictional heating, sublimation and re-condensation of grains free-falling into the solar nebula from a surrounding interstellar cloud. The sublimation model includes the effect of various volatile species, and accounts for the poor radiating properties of small grains using Mie theory. The amount of water ice sublimated, and the maximum grain temperature reached, vary over a wide range-- from 90% of the grain mass and 170 K at 30 AU from the nebular center to 0% and 50 K at roughly 1000 AU. The process of grain sublimation in the nebula is analyzed from the point of view of the nebular water vapor budget. We conclude that essentially all of the water sublimated eventually recondenses, because the cold nebular gas beyond 10 AU is able to hold only a small fraction as vapor. The adiabatic expansion of the sublimating gas from the grain surface leads to cooling and recondensation of most of the gas at nebular ambient temperature. Such a process in the 30-50 AU region would lead to at least two populations of primarily-water-ice grains: (1) essentially unaltered interstellar grains which did not sublime due to drag or accretion shock heating and (2) a component comprised of water ice co-condensed, after drag heating, with more volatile processed gases at nebula-ambient temperatures (~50 K), yielding volatile-rich amorphous phases with properties akin to the crystalline clathrate hydrates. Component (2) may be by far the most abundant in the outer solar nebula; the combination of (1) and (2) may explain the peculiar composition of comets relative to the interstellar medium and solar nebula models.

References: (1) Yelle, R.V., Lunine, J.I. and Hunten, D.M. *Icarus* 89, 347-358 (1991); (2) Stansberry, J., Lunine, J.I., Porco, C.C., McEwen, A.S. *Geophys. Res. Lett.*, 17, 1773-1776 (1990); (3) Kargel, J.S., Croft, S.K., Lunine, J.I. and Lewis, J.S. *Icarus* 89, 93-112 (1991).

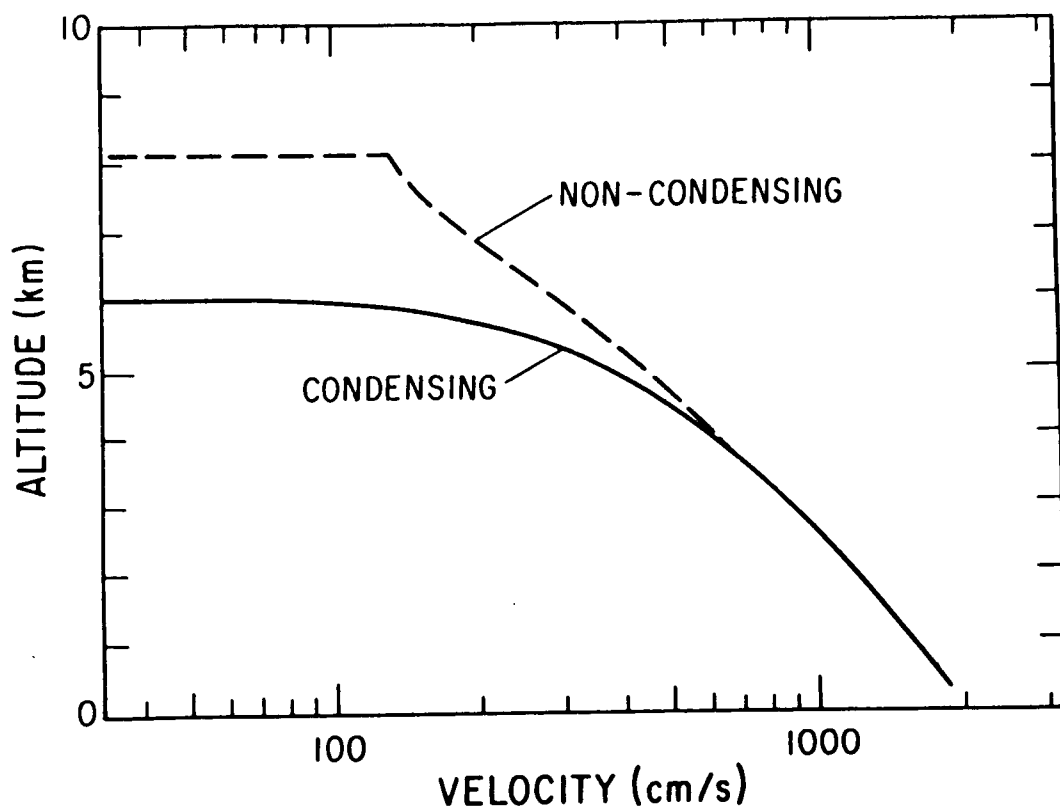


Figure 1. Upward velocity of a moist convective plume, for a surface geyser velocity of 20 meters/second. The line labeled "condensing" applies to an atmosphere which is saturated with nitrogen and has active condensation occurring; the other line applies to a slightly supersaturated atmosphere in which condensation is inhibited. From (1).

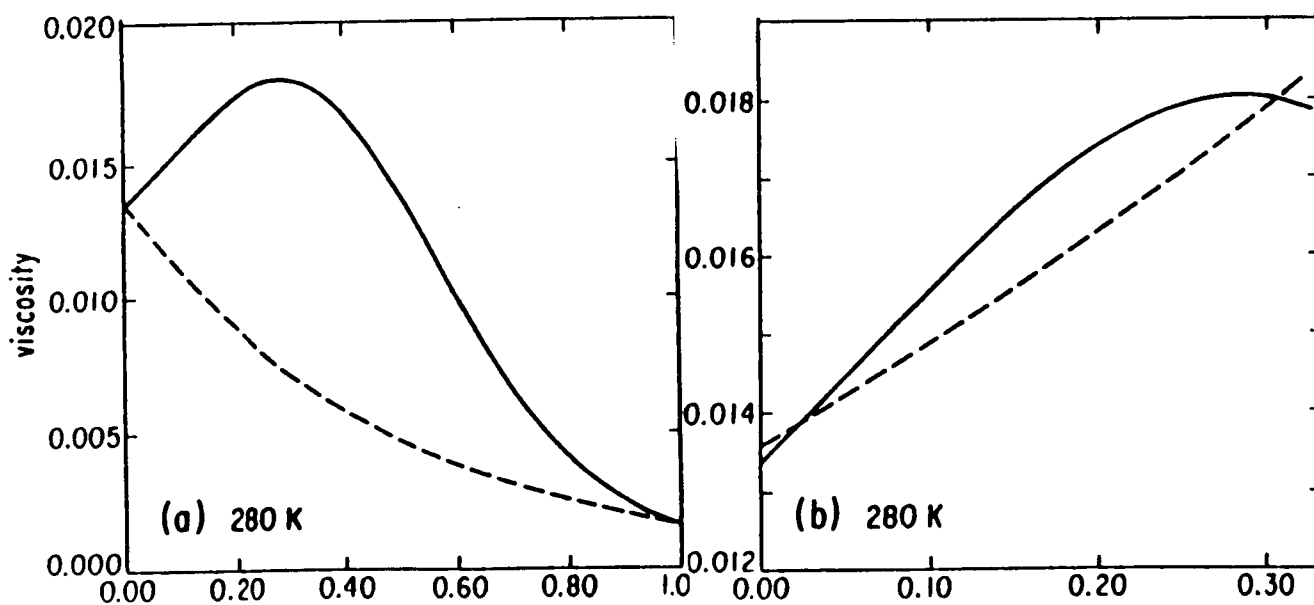


Figure 2. Viscosity (poise) versus ammonia mole fraction at 280 K is shown by the solid lines. The dashed lines are model fits assuming (left) a liquid composed of separate ammonia and water molecules and (right) a liquid in which the ammonia component is contained in ammonia-water clusters. From (3).